(1) Submission Title or Survey Name:
Galaxy clusters in 3D: a deep imaging survey of the Virgo and Fornax clusters.

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(4) Do you support the selection of a Roman Early-Definition Astrophysics Survey *(as described in the "Request for Information"; yes/no, with supporting motivation, 10 lines max)*:
yes. A Roman Early-Definition Astrophysics Survey is analogous to JWST Director's Discretionary Early Release Science (DD-ERS) call for proposals, when projects with community interest and demonstration of JWST science were solicited. Here one can think about a slightly different approach and carry out a survey, which not only will bear breakthrough science using unique wide-field capabilities of the Roman Space Telescope but will also further unlock its potential by performing all the required *Roman-specific scientific* calibrations of some widely used observational techniques, e.g. extragalactic distance indicators, reconstruction of star formation histories of galaxies or exoplanetary transit spectroscopy measurements using filters/grisms unique to the Roman telescope. Such a project will substantially accelerate the data analysis from future general observing programs and, hence, increase the scientific outcome of the Roman Space Telescope.

(5) Describe the science investigations enabled by the survey

We propose to carry out a complete deep 2-band imaging survey of the Virgo and Fornax clusters out to 0.5 (Virgo) and 1 (Fornax) virial radius using Roman WFI to obtain distances as precise as 1% [1, 2] to all member galaxies using the tip-of-the-red-giant-branch (TRGB) method. The dataset will provide near-infrared imaging of an area of 42 sq.deg. down to the limiting magnitude corresponding to $M_{\rm TRGB}+1.3$ mag at the Virgo/Fornax cluster distance. This unprecedented depth is currently achievable only with the Hubble Space Telescope WFC3/IR in a tiny 4 arcmin^2 field. The ground-based NIR surveys are hundreds of times shallower. The two main science drivers of our survey are: mass assembly of galaxy clusters and mass assembly of individual galaxies across the luminosity function. From this dataset we will build 3D maps of the two most nearby galaxy clusters at an unprecedented level of detail. Our proposal will address 5 main scientific questions.

(a) Thanks to resolved photometry, by using the source overdensity technique, we will identify nearly all low-luminosity cluster members down to the level of "ultra-faint dwarfs" in the Local Group and for the first time directly probe the bottom part of galaxy luminosity function in clusters, which will *provide a definitive answer to the "missing satellite problem" [3] of the Lambda-CDM cosmology.* (b) We will get 3D distances to all galaxies in Virgo and Fornax with available radial velocities and then run dynamical modelling *to recover mass distribution in the main components of both clusters and infalling subgroups* — it is known that adding 3D distances to radial velocities allow one to better break the degeneracy between orbital anisotropy and mass distribution, one of the main obstacles of accurate dynamical modelling. (c) We will have a complete census of the globular cluster (GC) and ultra-compact dwarf (UCD) galaxy population associated with each member galaxy. From a color-magnitude diagram, we will identify "red" and "blue" sub-populations of GCs down to the "GC survival mass threshold" ($10^{3.5}$ Solar masses) and measure their metallicities and then use them *to trace mass assembly of their host galaxies.* (d) We will for the first time assess the intracluster light in a resolved fashion which will provide *the best possible mass distribution estimate in the central part of the cluster.* (e) We will cross-calibrate TRGB and surface brightness fluctuations (SBF) distance indicators for Roman filter bandpasses which will open a new window of opportunities for *massive determination of redshift-independent distances to tens of thousands of galaxies out to 150 Mpc* in the High-Latitude Wide Area Survey because the SBF amplitude in the near-IR is much higher compared to the traditionally used optical bands.

Our survey can be considered as a deeper counterpart to the HLS in the 10% of the area. However, HLS does not reach the required depth to yield TRGB estimates beyond a few Mpc (comparable to the expected lower depth of Euclid). Our survey can be considered a much deeper and much higher resolution near-IR counterpart of the Next Generation Virgo Cluster survey [4] conducted with a 3.6m Canada-France-Hawaii Telescope, which reaches 1/10 of the depth in the optical and $<$1/100 of the depth in its K-band extension. Our proposed survey will produce: (i) high-resolution fully calibrated mosaic images of the Virgo and Fornax cluster; (ii) a catalog of member galaxies with TRGB distance estimates to those having a well populated red giant branch ($M_K < -10$); (iii) a catalog of compact stellar systems with a probabilistic association to host galaxies and estimates of metallicities and stellar masses; (iv) a color calibration of SBF distance scale for a chosen combination of WFI filters.

The open data policy will also enable a wide range of auxiliary science cases from the data collected by our survey, e.g. (a) luminosity functions of background groups and clusters of galaxies (there are dozens of them in the proposed survey area); (b) stellar streams around Virgo cluster galaxies; (c) Galactic brown dwarf population out to 2–3 kpc.

(6) Observational setup:
We propose to obtain a 100% coverage within 1/2 virial radius of the Virgo cluster ($r = 0.86$ Mpc= 3°) around Messier87 and a r =0.5 Mpc= 1.75° region around Messier49 (Virgo Southern subcluster) and 1 virial radius of Fornax (r=0.7 Mpc= 2.1°) using mosaic imaging with WFI in the $F087$ and $W146$ filters. Such a configuration (see Fig. 1) will allow us to reach 1 virial radius in the Virgo cluster in the southern direction and at the same time we will fit into a tentative allocation of 700 h for the total survey duration. We need to reach to the virial radius of each cluster to probe the diverse galaxy population at different radii subject to the morphology–density relation. With the proposed footprint we will cover 37.7 sq. deg. and 14 sq. deg. in the Virgo and Fornax clusters correspondingly. To reach the requested depth for TRGB distance estimates (see Fig. 2) at least 1.3 mag below the TRGB position for the most metal-rich stars (Solar metallicity), we need about 3 h of integration per field in Virgo (2 h in $F087$ and 1 h in $W146$) and 4.1 h in Fornax (2.75 h in $F087$ and 1.37 h in $W146$). Provided that a single WFI field covers 0.28 sq. deg. and giving a few per cent of the area for overlap / dithering, which reduces the effective footprint to 0.25 sq. deg., we will end up with 454 h in the Virgo cluster and 230 h in the Fornax cluster, or 684 h of exposure time for the entire survey.

(7) Preparatory activities:

- Our team possesses the largest collection of near-infrared stellar spectra of red giant and asymptotic giant branch stars to date (in the frameworks of X-Shooter Spectral Library and Las Campanas Stellar Library), which includes about 300 stars. Building a new generation of stellar population models in NIR is crucial for the theoretical calibration of both TRGB and SBF distance estimates. We might need additional observations at ESO VLT X-Shooter and Magellan MagE for low-metallicity RGB/AGB stars in Galactic globular clusters and Magellanic Clouds. The new stellar population models properly accounting for RGB/AGB contribution are also crucial for the interpretation of the GC/UCD colors and converting them into stellar metallicities.
- To get a reference for TRGB distances in the Virgo and Fornax clusters for our project, where only a dozen galaxies have been measured to date, we envisage to run a HST (or/and JWST) program to measure distances to a sample of $\sim 20-30$ galaxies in Virgo and Fornax covering a wide range of metallicities. The HST TRGB distance scale is very well calibrated; the calibration for JWST will become available soon. This will allow us to pin down possible metallitiсy-dependent biases when using the $F087$ Roman WFI filter instead of a much better calibrated HST ACS $F814W$. Our team has excellent expertise in the TRGB distance determination and calibration of the technique.
- To prepare a basis for dynamical modelling of Virgo and Fornax clusters using TRGB distances to thousands (hundreds) of predominantly faint galaxies (in addition to the literature data for brighter members) we will need to run a ground-based spectroscopic program to measure radial velocities of member galaxies. For faint targets we will use Magellan with IMACS and VLT MUSE and FORS2 in the Fornax cluster and Keck KCWI and LRIS, as well as MMT Binospec and BTA SCORPIO for the Virgo cluster. A subset of brighter galaxies will be observed using a Moscow University 2.5 m telescope. Our team members have institutional access to all the telescopes / instruments mentioned above except ESO VLT and BTA where we will apply for open time.

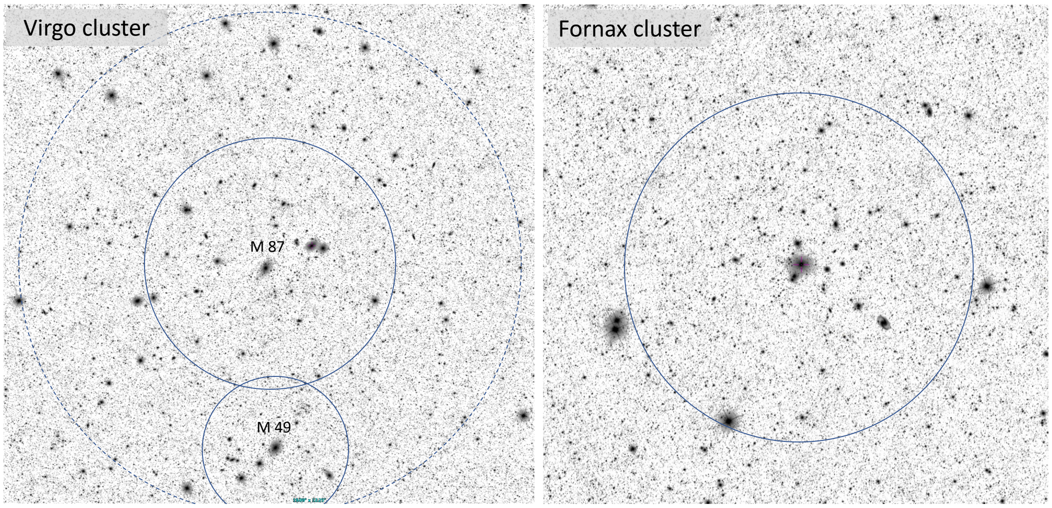

Figure 1: The proposed survey area (solid lines) for the Virgo (left) and Fornax (right) clusters. The images measure 12×12° (Virgo) and 6×6° (Fornax). The Virgo virial radius is shown by a dashed circle.

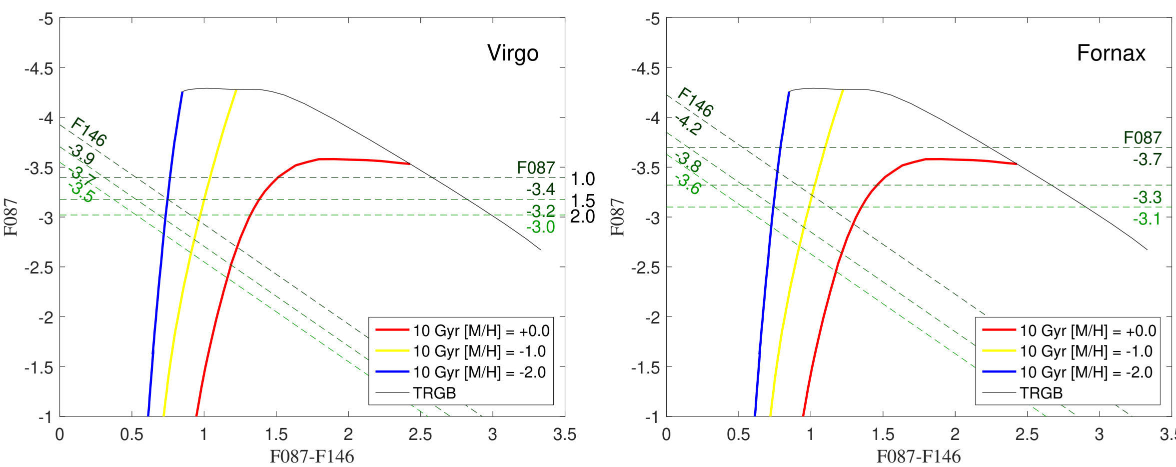

Figure 2: PARSEC [5] giant branch isochrones in the Roman Space Telescope $F087$ and $W146$ bands. The colored solid curves show the red giant branches of low and high metallicity for 10 Gyr stars. The right axis indicates the exposure time in hours required to reach the requested depth. The black line illustrates the $(F087-W146)$ color dependence of the TRGB. The green dashed lines show the expected photometric limits for different exposures indicated on the right axes at the distance of Virgo, $(m-M)_0 = 31.1$, and Fornax, $(m-M)_0 = 31.4$ mag, clusters. In 2 hours of integration we should reach stars about 1.3 mag fainter than TRGB at the distance of Virgo, and about 1 mag for the Fornax cluster. The TRGB [6] is one of the best standard candles based on Population II stars and it is extremely efficient to measure the distances in the nearby Universe [7]. The color dependence for the low metallicity stars is the smallest in the $F087$-band with the flux decrease towards red for high metallicity $[M/H] > -0.5$ stellar populations.

References

1. Rizzi, L. et al. Tip of the Red Giant Branch Distances. II. Zero-Point Calibration. ApJ 661, 815 (2007).

2. Jang, I. S. & Lee, M. G. The Tip of the Red Giant Branch Distances to Type Ia Supernova Host Galaxies. IV. Color Dependence and Zero-point Calibration. ApJ 835, 28 (2017).

3. Klypin, A. et al. Where Are the Missing Galactic Satellites? ApJ 522, 82 (1999).

4. Muñoz, R. P. et al. The Next Generation Virgo Cluster Survey-Infrared (NGVS-IR). I. A New Near-Ultraviolet, Optical, and Near-Infrared Globular Cluster Selection Tool. ApJS 210, 4 (2014).

5. Bressan, A. et al. PARSEC: stellar tracks and isochrones with the PAdova and TRieste Stellar Evolution Code. MNRAS 427, 127 (2012).

6. Lee, M. G. et al. The Tip of the Red Giant Branch as a Distance Indicator for Resolved Galaxies. ApJ 417, 553 (1993).

7. Anand, G. S. et al. The Extragalactic Distance Database: The Color-Magnitude Diagrams/Tip of the Red Giant Branch Distance Catalog. AJ 162, 80 (2021).